Chapter 8: Impedance studies

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Evaluating auditory function in adults is normally a reasonably straightforward procedure. Except where deliberate efforts are made to deceive, or where the subject is seriously ill or mentally incapable, cooperation can be depended on even in complex and time-consuming listening tests.

With children, especially babies and infants, even passive toleration of simple test procedures cannot be presumed or relied upon. Consequently, for many years there has been a search for so-called 'objective methods' of assessing hearing and auditory status that require no voluntary involvement of the test subject.

Almost 200 years ago, changes of infant behaviour in response to sound were reported by Tiedeman (1789), whose 13-day-old son was observed to give attention to those who spoke to him and whose 'crying could be somewhat hushed by soothing speech'. Charles Darwin (1877) wrote, of his son born in 1840: 'He often started on hearing sudden sound, and blinked his eyes'. Two responses to acoustic stimulation are noted here: startle and eye-blink. Until relatively recently, detection of hearing loss in infants has depended upon such involuntary responses. These tend to be inconsistent and the differentiation of a sound-provoked response from an adventitious movement is extremely difficult even with highly skilled and adequately self-critical observers. Today the trend is to transfer the decision-making process to a microprocessor, as in the auditory response cradle (Bennett and Wade, 1980). Where there is suspicion of hearing loss, estimation of hearing level may be obtained by non-invasive, objective techniques such as electric response measurement.

However, such sophisticated evaluative methods are not really practicable in the clinical setting. Faced with a small, distressed child and a worried and perhaps equally distressed mother, what can the clinician employ for evaluating the auditory system? Traditionally there have been two basic approaches: visual examination and the use of some type of sound-response assessment. Looking at the ears has limitations; the tympanic membrane is almost opaque, and although interferences may be made about middle ear conditions, virtually nothing can be deduced about the inner ear status by direct vision down the external canal. Response to sound is subject to the limitations noted above for babies, and children up to the age of 2.5-3 years are difficult to assess accurately, even by skilled personnel.

It was probably with some such thoughts in mind that a German otologist, Dr August Lucae, investigated an alternative method of auditory examination. In 1867, he published a paper describing the use of the 'interference otoscope', a device that employed sound itself as the investigating medium. From these pioneering studies has developed the modern range of acoustic impedance measuring systems that can be found in routine use in every otolaryngology department.
Rationale of acoustic impedance/admittance measurement

Underlying Lucae's observations was the concept that the normal ear efficiently absorbs the acoustic energy falling on it and that any malfunction in the mechanical system of the middle ear would affect the efficiency of absorption. To a substantial degree, the same concept lies at the heart of the current techniques for assessing auditory function by evaluating the acoustic impedance of the ear.

The middle ear is an impedance matching device for optimizing the transfer of acoustic energy from the gaseous medium of sound transmission, air, to the much denser fluid medium of the inner ear. Without the middle ear, at least 97% of the incident energy would be reflected at the oval window. The mechanism by which the middle ear reduces this potential loss of energy is primarily by gathering sound at low pressure over the relatively large area of the tympanic membrane and transmitting it into the cochlea over a much smaller area, at higher pressure through the footplate of the stapes. The tympanic membrane has an effective area which is about 18 times that of the footplate. Furthermore, there is a beneficial level effect due to the malleus being longer than the incus. This leverage ratio is about 1.3:1, so in total the middle ear has an amplification factor of 18 x 1.3 - approximately 23 times, equivalent to 27 dB, that is 20 log 23.

This basic view of the function of the middle ear assumes that the tympanic membrane operates as a simple piston. In fact its operation is far more complex, especially at frequencies higher than 2 kHz, since above this frequency progressively less of the membrane is coupled to the manubrium. Hence the efficiency of the middle ear system varies according to the frequency of the incident sound. It is also highly dependent on the condition of the many component parts that make up the middle ear transmission system.

An impaired middle ear will function differently from normal in relation to the sound incident upon it. If the impairment is one that causes an increase in stiffness, then the tympanic membrane will be less able to respond to the pressure changes that constitute a sound stimulus. It will, relative to a normal ear, present a greater impedance to the passage of sound to the cochlea and it will effect a lower admittance of sound. Conversely, an abnormally mobile system, for example that occurring when the incudostapedial joint is disrupted may absorb or admit proportionately more energy than a normal middle ear, although this will not be transmitted to the cochlea because of the break in the ossicular chain. Lucae hypothesized, and indeed established, that some indication of the status of the middle ear might be made by examining the manner in which the tympanic membrane admits or impedes sound falling on it.

Principles of acoustic impedance/admittance measurement

The middle ear is a mechanical system and can, from a mechanical standpoint, be regarded as consisting of three component types: mass, elasticity and friction.

In the middle ear the major components involving mass are the ossicles, in particular the malleus and incus, with lesser contributions coming from the tympanic membrane, the suspensory ligaments of the ossicles and the stapes.
Elasticity is provided by (a) the tympanic membrane, essentially from its radial fibres, (b) the volume of gases contained in the middle ear cleft which is compressed on inward movement of the drum and rarefied by outward movement such that it always acts to restore equilibrium, (c) by the suspensory ligaments, and (d) to a lesser extent by the incudostapedial joint and the cochlear windows.

Friction is inevitable in all dynamic systems, human as well as purely mechanical. It occurs throughout the middle ear mechanism.

The three types of mechanical component react differently to an applied oscillating force such as sound. Friction or resistance is responsible for energy loss and is virtually constant regardless of the frequency of the excitation. The mass and elasticity and stiffness components do not cause the loss of energy; instead they convert motion into kinetic or potential energy depending on the phase relationship with the stimulus. At low frequencies the elasticity is dominant, at high frequencies mass dominates.

Pathologically the mass elements of the middle ear are rarely altered. The ossicles rarely change appreciably in size or weight. The tympanic membrane may become thickened, but the overall change in the mass of the middle ear system is small. The situation is very different with regard to the elasticity elements. In otosclerosis the elasticity of the stapedial footplate is effectively reduced to zero. With the stapes immobile, movement of the incus/malleus is greatly inhibited, and this inhibition of movement is transferred to the tympanic membrane. Incident sound energy is then less freely admitted into the middle ear system. Likewise, in adhesive otitis, ossicular movement is restricted by the fibrous tissue, and the capacity of the tympanic membrane to move freely is reduced; the impedance it presents to incident sound energy is increased. An opposite effect is observed when the incudostapedial linkage is severed. Under such circumstances the incus/malleus is less constrained in its movement than in the normal ear, and the tympanic membrane is therefore more compliant than normal. If the eustachian tube is functioning poorly and the gas pressure within the middle ear is below normal, the tympanic membrane will be indrawn and the fibres will be stretched so stiffening the membrane. An opposite effect occurs if, through long-standing disease, the tympanic membrane loses its radial fibres. It then becomes flaccid and abnormally compliant.

Changes in mass are rare; changes in stiffness or elasticity are common. In order to maximize the efficiency in detecting disorders of the middle ear by examination of the system's response to acoustic stimulation, the most useful information will, therefore, be obtained by employing sounds in the low auditory frequency range.

The basic layout of an acoustic device for assessing efficiency of sound reception of the middle ear is shown in the figure. A low frequency tone is generated by an oscillator and, after amplification, is introduced into the ear canal. Here some energy will be absorbed and some reflected and, if the middle ear is efficient, the amount reflected will be low. It will be raised if the tympanic membrane is stiffened thereby presenting a greater impedance to the ingress of sound and it will be reduced below the normal level if the tympanic membrane is flaccid or hypermobile. Hence, the sound pressure level in the ear canal will depend on the impedance or admittance of the middle ear detected at the tympanic membrane. This level can
be detected and measured by means of a microphone, the output from which will indicate the status of the middle ear in terms of its elasticity.

Such a simple system has a number of limitations. If the tympanic membrane is highly absorbent, the sound pressure level in the canal may be so low that other physiological noises interfere with the accurate measurement of the 'reflected' sound. If, to overcome this difficulty, the input sound level is raised, the possibility of stimulating the stapedius muscle arises. However, should this happen, the stiffness of the system will be increased and the measured status will then not represent the normal condition of that ear.

To overcome these measurement difficulties, it is now the practice to maintain the ear canal sound pressure level at a constant value high enough to avoid interference from physiological noise, but not so high as to trigger a contraction of the stapedius muscle. In such a system, the input level is closely related to the impedance/admittance of the middle ear. If the tympanic membrane is stiffened (of itself, or in response to conditions within the middle ear), it will present a high impedance to sound. The admittance of sound into the middle ear will be low and hence, to reach the chosen sound pressure level in the ear canal, it will be necessary to provide only a small amount of amplification. The opposite will apply when the tympanic membrane is flaccid and absorbent, much more energy having to be provided by the amplifier to maintain the chosen sound pressure level in the ear canal. Thus, a direct relationship exists between the gain of the amplifier and the impedance/admittance to the middle ear measured at the tympanic membrane.

Up to this point the terms 'impedance' and 'admittance' have been employed without clear definition. Acoustic impedance refers to the inhibition of acoustic energy flow. Admittance is the reciprocal and indicates the readiness of the system, the middle ear in this situation, to allow the flow of acoustic energy. Both terms appear in the voluminous literature, often seemingly in an almost interchangeable fashion. Historically 'impedance' was the first term to gain acceptance, but 'admittance' is now becoming the accepted term, and will be used hereafter in this text.

Tympanometry - basic principles and classification

One of the functions of the eustachian tube is to maintain the pressure in the middle ear at, or very close to, atmospheric pressure. Only when the pressure is the same on both sides of the tympanic membrane will the membrane be completely free from stress and hence at its most efficient. It will then, and only then, admit the maximum amount of acoustic energy to the middle ear. If the pressure either in the middle ear or in the external meatus changes, tensions will arise in the radial fibres. The membrane will stiffen and the admittance of acoustic energy will diminish. Observations indicate that a pressure differential across a normal tympanic membrane of 0.5% of atmospheric pressure (50 mmH₂O or 50 decapascals (daPa)) will almost halve the admittance. A pressure differential of 2% is sufficient to render the tympanic membrane effectively acoustically rigid.

In the majority of modern electroacoustic impedance measuring instruments, means are provided to alter the pressure in the ear canal in a controlled and quantified manner. Tympanometry is the graphical representation of the admittance (or impedance, or compliance) of the middle ear as a function of the pressure load applied to the tympanic
membrane. There is an almost infinite range of variation of shape in tympanograms, but certain patterns tend to be associated with specific middle ear conditions.

The normal middle ear produces a peaked curve that is almost symmetrical about the point of maximum admittance. A typical tympanogram obtained from a normal middle ear is shown in the figure. The abscissa indicates the pressure in the ear canal relative to the ambient (atmospheric) pressure and the ordinate shows the magnitude of the acoustic admittance detected by the instrument at the tip of the probe which is hermetically sealed into, or at the entry to, the ear canal. Between the probe tip and the tympanic membrane is a volume of air, the magnitude of which will depend on the size of the individual's ear canal and the depth of insertion of the probe. This air has an elasticity which is directly related to its volume, and which 'adds on' to the elasticity of the middle ear. However, when the air pressure in the ear canal is more than 2% different from the pressure in the middle ear, the tympanic membrane is, as noted above, effectively rigid. The admittance of sound into the middle ear is reduced to almost zero. Under these circumstances the admittance measured by the instrument is attributable to the air in the ear canal. Its effect can be estimated in this manner and, by subtraction, the true admittance of middle ear can be derived.

Thus, from a tympanogram, one can calculate:

1. the volume of the ear canal medial to the probe tip (A-B)
2. the admittance of the middle ear, that is the difference in admittance from the stressed to the completely unstressed condition of the tympanic membrane (B-C)
3. the middle ear pressure, which is the same as the ear canal pressure for maximum admittance.

If a middle ear with otosclerosis is considered, when the pressure differential across the tympanic membrane is more than 2% the tympanic membrane is, as in a normal ear, effectively stiff and the admittance falls to almost zero. If the pressure differential is removed, the admittance rises to a maximum, but this will not be as great as for a normal ear due to the loading imposed on the tympanic membrane by the fixation of the stapes and the consequent reduced mobility of the major ossicles. The result is a smaller, shallower tympanogram. Conversely, in an ear where the incudostapedial joint is disrupted, the tympanic membrane may be more than normally mobile. The resulting tympanogram may be higher than normal and a similar tympanogram may be obtained from an ear where the tympanic membrane is hypertrophic.

Caution needs to be exercised in drawing conclusions from the size of tympanograms. Otosclerosis tends to produce shallower curves and thinning of the tympanic membrane tends to produce deeper curves. Thus an ear in which the two conditions coexist may produce a tympanogram that is normal in size.

If the eustachian tube is underfunctioning so that the gas pressure in the middle ear falls below normal, then the tympanic membrane is stiffened. The stress on the tympanic membrane is completely removed only when the pressure in the external ear canal is exactly equal to the pressure in the middle ear. The tympanogram for an ear with this condition has
the same shape as that for a normally functioning ear except that the peak admittance is
displaced in the direction of reduced pressure to a degree that indicates the reduction in
pressure in the middle ear. In children, negative pressure in the middle ear is frequently
followed by effusion. The whole of the middle ear cleft may be filled with a fluid that
severely damps movement of the tympanic membrane. The tympanogram produced by an ear
with effusion is typically low and flat with a maximum admittance at some degree of negative
pressure.

When the tympanic membrane is not intact, a pressure differential cannot be created
and maintained between the ear canal and the middle ear. A virtually flat tympanogram is
then obtained. This can be valuable in indicating a perforation not visible to the naked eye.
It can also be employed to assess the status of a ventilation tube, that is whether it is patent
or blocked.

Tympanograms that vary over short periods of time can have diagnostic significance.
If the variation is synchronous with respiration, the most probable cause is a patent eustachian
tube. The air pressure in the middle ear then varies according to whether the subject is
inhaling or exhaling: the pressure differential across the tympanic membrane similarly varies,
and the admittance rises and falls in time with the breathing. A faster variation, synchronous
with the pulse, is sometimes seen where there is some acute inflammation of the middle ear
or tympanic membrane. More rarely it may indicate a glomus tumour (Black et al, 1979).

In an effort to improve the diagnostic potential of tympanometry, Brooks (1968)
quantified tympanograms using three parameters: these were compliance (the height of the
tympanogram: equivalent to the admittance), the middle ear pressure indicated by the peak
of the curve, and the shape, this being defined in terms of the 'gradient' of the tympanogram
around the point of inflection. With this three measurements almost any tympanometric curve
could be numerically defined and, if so desired, reconstituted graphically.

Jerger (1970) devised a different classification system that was based essentially on
subjective judgement of the shape of the curve. He divided tympanograms into three basic
shapes: that obtained from a normal ear was designated 'type A'. The flat curve typical of an
ear loaded with effusion was designated 'type B'. The curve of normal shape, but displaced
in terms of reduced pressure, was designated 'type C'. After a little experience with these
limited options, it was recognized that the range of variation of tympanograms was such that
further subdivision was needed. Exceptionally deep tympanograms were therefore designated
as 'type A_d', and very shallow ones as 'type A_s'. The Jerger classification has been widely
adopted in the USA; it has a simplicity that is superficially appealing, but it is imprecise and
does not lend itself to mathematical analysis.

Middle ear muscle reflexes: basic principles

Tensor tympani muscle

The role of the tensor tympani muscle in audition is still largely conjectural, despite
much research. Contraction in response to sound only occurs when the intensity is such as to
cause a generalized startle reaction (Djupesland, 1965). The effect of contraction of the tensor
tympani on the admittance of the middle ear is inconsistent both between and within subjects. Consequently evaluation of tensor tympani function has very limited diagnostic potential.

**Stapedius muscle**

Contraction of the stapedius muscle produces a stiffening of the ossicular chain observable as a decrease in the admittance of sound at the tympanic membrane. In the mid-frequency range a sound of 85 dB (±10) above the normal hearing threshold is sufficient to elicit a detectable response, and this sound level is defined as the acoustic reflex threshold (ART). Contraction can be elicited by a variety of forms of stimulation. Touching the skin close to the auricle elicits a homolateral contraction that fatigues rapidly (Djupesland, 1965). Low voltage electrical pulses applied to the ear canal also result in stapedius muscle contraction in most normal middle ears, but the stimulus tends to be at least uncomfortable and sometimes painful; hence this is not a procedure that is acceptable for the testing of children.

Acoustic stimulation has proved to be a simple, effective and acceptable method of eliciting reproducible responses from the stapedius muscle. The reflex centre is believed to be in the superior olivary complex. Afferent signals from the cochlea are assessed and, when certain conditions are met, efferent signals pass by way of the seventh nerve to the stapedius muscle to initiate a response. The conditions for emission of efferent signals in response to acoustic stimulation appear to be dominantly related to the loudness of the sound - the subjective correlate of intensity.

Klockhoff (1961) stated that a detectable stapedius reflex indicated a middle ear free from mechanical defect, that is free of conductive dysfunction. Otosclerosis, fibrosis, middle ear effusion, atelectasis, ossicular discontinuity, even quite small degrees of reduced middle ear pressure will normally stiffen the middle ear system so much that no stapedius muscle reflex can be detected. According to Jerger et al (1974a) an air-bone gap of only 5 dB in the ear in which the muscle response is being observed will, in about 50% of subjects be sufficient to suppress the reflex. An air-bone gap of 10 dB reduces the likelihood of a reflex to less than 25%. However, in a very small number of middle ears, acoustically induced reflexes can be elicited even in the presence of a substantial conductive hearing loss. Subsequent observations have largely, but not entirely, confirmed Klockhoff's original statement. The situation now is that a detectable stapedius reflex indicates with a better than 95% probability that the middle ear is within normal limits.

Absence of stapedial reflex does not, however, necessarily indicate a middle ear lesion. It is possible that: the stimulus may not be adequate, the ascending tract of the eighth nerve may be impaired, there is some central lesion, the descending motor channel via the seventh nerve may be malfunctioning, or the stapedius muscle is non-functioning, a condition that appears to exist in a small percentage of otherwise completely normal individuals.

**Limitations of admittance measurement**

Keith (1973) tested 40 normal babies from 36 to 151 hours of age with an admittance system with a probe frequency of 220 Hz. In the ears of seven infants he observed 'W'-shaped tympanograms which are rarely seen in older individuals, and are almost invariably associated
with an abnormally compliant system. It seems probable that the external canal of the infant lacks the rigidity of the more mature child or adult and consequently the acoustic characteristics of the meatal walls alter during the pressure changes employed in tympanometry. Paradise, Smith and Bluestone (1976) studied the correlation between tympanometry and otoscopy in infants. Agreement was good in older subjects, but below 7 months of age correlations were poor. Of 40 ears with effusion confirmed later by myringotomy, 24 displayed normal tympanograms. The conclusion drawn from these findings is that tympanometry on subjects under 7 months of age is of doubtful reliability.

Early studies on the acoustic stapedial reflex in infants seemed to indicate similar problems. One of the earliest published studies on admittance measurement in children (Robertson, Peterson and Lamb, 1968) was concerned with the acoustic reflex. At the age of 12 months, only three out of 10 children tested produced stapedius reflex responses to acoustic stimulation. In older children (from 18 to 36 months), stapedial reflex responses were obtained in about 70% of those tested. Bennett (1975) tested 98 babies ranging in age from 5 to 218 hours and was able to obtain acoustic stapedial reflexes from only 16%. Newman, Stream and Chesnutt (1974) reported that in many infants the stapedial reflex did not emerge until as late as age 9 weeks, a supposition receiving support from Keith and Bench (1978) who suggested that the reason for lack of reflexes in such a high proportion of neonates was immaturity of the neurological mechanism. However, Bennett and Weatherby (1980) in a study of 44 neonates aged from 10 to 169 hours indicated that absence of measurable response was more likely to be a function of the probe frequency of the admittance measuring system. Prior to this study, researchers had used a conventional admittance measuring system with a probe frequency of around 220 Hz. Bennett and Weatherby employed a detection system having a variable probe frequency. As the frequency was raised from 400 to 800 Hz, the percentage of observable reflexes increased, reaching 100% at 800 Hz. The most probable reason for the lack of acoustic reflexes at 220 Hz is, as with the 'W'-shaped tympanograms, that the middle ear of the neonate is markedly more flaccid than that of the older child or adult.

There are few other limitations to admittance measurement in children. Atresia of the external auditory meatus renders the test ineffective. Perforation of the tympanic membrane rules out tympanometry in that no pressure differential can be maintained across the membrane. For the same reason no acoustic reflexes can be detected.

Hyperactive children are difficult to test even with modern high-speed automatic recording admittance equipment. It may prove impossible to insert the probe into the ear or even hold it against the ear for the 3-4 seconds required for the instrument to gather and store the data. For such children, the acoustic reflectometer (Teele and Teele, 1984) may be appropriate, providing some basic data about middle ear status in about one-tenth of a second and without the need for airtight sealing of the probe tip into the ear canal.

Admittance measurement: evaluation of conductive disorders

General

In congenital disorders of the conductive mechanism, admittance measurement has limited value due to the gross abnormalities in the middle ear structures. Fortunately, such
disorders are rare and the abnormalities, if not obvious otoscopically or physically, may often be inferred from external manifestations.

Otosclerosis, neoplasm, fibrosis and disruption of the ossicular chain occur very infrequently in children. Where they do occur, admittance measurement may add to the information gathered from the history and clinical examination.

**Otitis media**

Unquestionably the commonest condition affecting the middle ear system that results in a conductive dysfunction is otitis media. This may be acute or chronic: with or without perforation. The acute condition is usually seen and treated at the level of primary medical care. Perforation in children is no longer a common occurrence. But chronic otitis media with effusion (see Chapter 12) is a very common condition and admittance measurement has a significant role to play in the detection and treatment of this condition.

**How can otitis media with effusion best be detected?**

Admittance measurement appears at present to be the technique possessing the best potential for identifying children with otitis media with effusion. In 1977, a Symposium on Impedance Screening was held at Nashville, Tennessee (Harford et al, 1978). A task force of 28 experts considered the state of the art and strongly encouraged the use of the technique for research studies. The majority did not advocate the immediate introduction of mass screening, partly because screening should not be introduced until adequate support services are available and partly because of uncertainties about the effectiveness of treatment and possible risks of overaggressive treatment (Black, 1985). However, even though the effectiveness of medical or surgical intervention may be in doubt, early detection is desirable in order that parents and teachers may know that a child is hearing impaired, albeit only slightly, and not lazy, inattentive or naughty. Simple remedial action can then be taken to minimize the effects of the hearing loss. A single admittance screening in schoolchildren would, however, not only identify children with chronic otitis media with effusion, but also those with transient conditions that will recover spontaneously. To overcome the otherwise excessive rate of over-referral, a two-tier screening system is desirable (Brooks, 1978). Such a scheme has been employed and shown to be highly effective in identifying children in need of attention without causing overload of the otolaryngological services (Ferrer, 1983).

**When should admittance screening be performed?**

In the long-term studies on otitis media with effusion carried out by the author (Brooks, 1976), it was noted that the children who had the most persistent middle ear effusions had, in contradistinction to all the other children in the study, clear indications of otitis media with effusion at the first admittance test which was carried out within days of their entry into full-time schooling. In other words, these children already had chronic otitis media with effusion. It seems quite likely that they belong to the group of children described by Howie, Ploussard and Sloyer (1976) as 'otitis prone'. This condition appears to develop very early, certainly during the first 2 years of life. Whether screening could be effectively employed to identify 'otitis-prone' children at this early stage, and whether this would improve
prognosis remains to be established. The logistic problems of such an early screening programme are certainly formidable.

Special need groups

**Children with severe sensorineural hearing loss**

There has been an assumption for many years that the worst possible auditory condition a child can experience is severe or profound sensorineural hearing loss, and undoubtedly this does present enormous problems to the educator and can greatly affect the quality of life of the individual.

Early identification and remediation with high quality amplification systems greatly improves the prognosis. Conversely anything that reduces speed or effectiveness of remediation will diminish the prospects of effective habilitation. The additional hearing loss associated with otitis media with effusion is a factor that professionals involved with the severely hearing impaired have, in the past, tended to overlook.

Brooks (1974) employed admittance measurement to test 306 children who were in residential schools for the deaf in 1969. The prevalence of otitis media with effusion at age 5 was the same as in normally hearing children of the same age, that is about one child in five had otitis media with effusion on the day of test, the child otherwise appearing to be in good health. As with normal hearing children, the prevalence diminished with increasing age, but the rate at which it diminished was slower, and at age 11 approximately 7% of the children still had tympanograms that strongly suggested effusion in the middle ear. This compares with only 2% in normal hearing children of the same age.

A number of other studies (Porter, 1974; Mehta and Ehrlich, 1978; Newall and Campbell, 1978; Stool, Craig and Lord, 1980) support the finding of high prevalence of middle ear disorders in children with severe sensorineural hearing loss. Inevitably the hearing levels of children with otitis media with effusion will be further depressed. Even without any middle ear dysfunction the hearing levels of many children in such an educational setting is such that hearing aids and earmoulds are working at the very limit of performance. The added loss occasioned by otitis media with effusion is likely to diminish substantially the effectiveness of the aid, probably resulting in acoustic feedback, high levels of distortion and gross loss of performance.

Hence for children with known severe/profound hearing loss, regular monitoring with admittance measurement is advisable, and early referral for management vital (Milner, Weller and Brenman, 1985).

**Down’s syndrome**

For all Down’s syndrome patients with hearing loss, especially those with intractable middle ear dysfunction, hearing aids should be considered as a practicable and beneficial option. As Balkany et al (1979) stated, retarded children use aids well and are helped by them as much or more than otherwise normal children.
Likewise, admittance testing should be a regular feature of the management of Down's syndrome children, in order that middle ear malfunctions can be identified as soon as possible and treatment provided and monitored.

**Cleft palate children**

According to Doyle et al (1984): 'Children with cleft palate are considered to be at risk for the development of otitis media with effusion with an incidence approaching 100 per cent.' An inevitable consequence of this will be a high incidence of hearing loss, and this is confirmed by Jarvis (1976) who, in a study of 350 children with cleft palate, found that at least half the children had a hearing loss in one ear exceeding 20 dB at some time, and that 35% were likely to have a permanent defect. Bess, Schwartz and Redfield (1976) showed that admittance measurement was effective in identifying middle ear dysfunction in cleft palate children, correlating highly with otoscopy.

**Others**

The truly autistic child is, fortunately, rare as are children with central nervous system disorders. In such children admittance measurement can add to the diagnostic information (Petersen, 1978). It bears repeating that children with severe physical or mental disorders are not precluded thereby from the additional difficulties imposed by otitis media with effusion. Where cooperation in testing is not readily forthcoming, admittance testing will normally provide accurate, repeatable information on middle ear function with the minimum of difficulty.

**Monitoring of treatment**

Insertion of ventilation tubes in the tympanic membrane is the most frequent surgical procedure employed in the treatment of otitis media with effusion (Black, 1985). Postoperative tympanometry can be helpful in determining the effectiveness of the ventilation tube. In an ear with an intact tympanic membrane the compliance or admittance measurement obtained with the membrane fully stressed with either positive or negative pressure, is the volume of the ear canal. In children this is usually less than 1 mL. Only rarely will it exceed 1.5 mL. If, when testing an ear with a ventilation tube, a straight-line tympanogram is obtained with, at the same time, indications of a larger than normal volume (over 1.5 mL), then the probability is that the ventilation tube is in place and functioning as a perforation. The large volume is due to the coupling of the middle ear space to the ear canal through the ventilation tube.

If the ventilation tube is blocked and there has been recurrence of the effusion then a typical flat (type B) tympanogram will be obtained. If the ventilation tube has been extruded and the tympanic membrane has healed the tympanogram patterns will be the same as with an intact tympanic membrane.

**Evaluation of eustachian tubal function**

If tympanoplasty is being considered, it may be helpful to have some indication of the functional state of the eustachian tube. It is possible to apply positive pressures from the
admittance instrument to the sealed ear canal and to observe at what pressure the tube is forced open to allow the passage of air into the nasopharynx. However, this is not a physiological test. The eustachian tube normally operates against a negative pressure gradient. A more realistic approach is, therefore, to reduce the pressure in the ear canal to, say, -200 daPa (or -200 mmH₂O) and then ask the subject to swallow. If the tubal function is good, then with each swallow the negativity of the pressure is reduced. In perhaps four or five swallows the pressure is restored to normal atmospheric pressure.

Sometimes, although the tube opens and more air enters initially, a plateau is reached beyond which no further normalization occurs. The nearer this plateau is to atmospheric pressure, the more normal the function of the tube is likely to be.

**Admittance measurement: evaluation of sensorineural disorders**

**Identification of sensorineural hearing loss**

Norris, Stelmachowicz and Taylor (1974) studied the response of the stapedius muscle to pulsed auditory stimulation in a series of normal and sensorineurally hearing impaired children. A difference in the pattern of response between the two groups was identified. The normally hearing ears followed the modulation of the stimulus, but the stapedius muscles in the sensorineurally impaired ears tended to remain contracted in the inter-stimulus intervals. Parameters for the stimulus were suggested that would assist objectively in determining from admittance measurement of the acoustic reflex whether an ear under test was close to the normal limit for hearing, or whether there was a substantial degree of hearing loss. The test procedure did not give any finer degree of resolution of hearing loss, and so appeared to have limited applicability.

In the same year, Niemayer and Sesterhenn (1974) demonstrated that some estimate of degree of hearing loss might be made by measuring the reflex threshold for pure tones and for broad band noise. Earlier research had shown that the threshold for band noise was lower (quieter) than the threshold for pure tones in normal hearing subjects. Niemeyer and Sesterhenn observed that, as the severity of the sensorineural hearing loss increased, the difference between the thresholds of the acoustic reflex to tones and noise diminished.

The basis for this phenomenon is thought to be related to the number of critical bands stimulated by the broad band noise. It is conjectured that, in the impaired ear, the number of bands is reduced due to the widening of the individual bands.

Jerger et al (1974b) used this technique to predict hearing levels in 1043 subjects ranging in age from 3 to 91 years. No attempt was made to determine the actual hearing level in decibel terms, but hearing loss was categorized as either normal, mild to moderate, severe or profound. Correct assignment to category was achieved in just over 60% of subjects. A one-category error was made in approximately 35% of subjects. In just over 4% of those tested a two-category error was made designating severe losses as normal or vice versa. Fortunately, the majority of the errors were such as to overestimate the degree of impairment - a 'safer' type of error than the reverse whereby the parents of a child with a severe loss might be falsely reassured as to the degree of hearing ability. Efforts were made to add
information about the shape of the audiogram as well as the degree of loss, but these proved to be of little value.

Several other attempts have been made to assess hearing level from the acoustic reflex to tones and noise bands (Popelka, 1981). No one method stands out as being superior in its ability to predict the actual level of hearing.

In 1977, Sesterhenn and Breuninger described a new method of assessment wherein a high frequency (8000 Hz) tone was used to 'pre-activate' the stapedius muscle. The reflex-eliciting threshold for this tone is first determined and then the intensity of the tone is reduced to just below that level. A second tone of lower frequency (between 250 and 4000 Hz) is then introduced at the same time and into the same ear as the pre-activating tone.

The reflex-eliciting threshold is determined by adjusting the intensity of the low frequency tone while maintaining the intensity of the pre-activating tone at the just-subthreshold level. Under this condition of two-tone stimulation, the level of the lower tone is found to be somewhat below the intensity required to elicit a reflex when that tone is presented alone. The difference between the thresholds under the two test conditions can be related to the hearing threshold at the frequency of the lower tone. The single frequency accuracy obtained by Sesterhenn and Breuninger was such that 65-79% of the results were within 10 dB of the true threshold and 87-98% were within 20 dB. Brooks and Ghosh (1982) produced results of similar accuracy employing this technique. For the five frequency average (250-4000 Hz) 89% of results were within 10 dB of true threshold.

However, Brooks and Ghosh (1982) expressed reservations about the clinical applicability of this test. The procedure is time consuming, taking around 15 minutes per ear. The signal levels are high and may temporarily cause tinnitus. The test would not be tolerated by young children or the mentally subnormal, two of the groups for whom such a test would be most applicable. Refinements may be possible to improve the test procedures but, at present, application seems to be limited to evaluation of non-organic hearing loss.

**Assessment of recruitment**

Recruitment of loudness is generally regarded as indicating the probable locus of pathology in the cochlea. Dix, Hallpike and Hood (1948) suggested that patients with sensorineural hearing loss without recruitment had a retrocochlear lesion and those with recruitment had a lesion that was essentially cochlear in origin.

Thus the presence or absence of recruitment was perceived as a vital factor in the differential diagnosis of cochlear versus retrocochlear hearing loss. The classical test for recruitment of loudness is the alternate binaural loudness balance (ABLB) test in which a series of loudness balances is obtained between the two ears of the subject. The ABLB test depends on the willingness and ability of the patient to make the series of judgements of loudness, this often being made more difficult by the presence of diplacusis.

As early as 1952, Metz proposed the use of acoustic reflex measurements for assessing recruitment. He observed that in normal hearing subjects the threshold of the reflex for contralateral stimulation was around 85 ± 10 dB. In patients with sensorineural hearing loss
the reflex could be elicited with little elevation of the intensity of the stimulus, despite the reduction of threshold sensitivity in hearing. Metz suggested that, if the difference between pure tone hearing threshold and acoustic reflex threshold was less than 60 dB, then recruitment of loudness was present.

One merit of the acoustic reflex test for recruitment as compared to the ABLB test is objectivity. The patient no longer has to make difficult loudness judgements. The reflex response is automatic and repeatable. The test is quick and easy to employ. It can also be employed in cases of bilateral hearing loss where the ABLB test may be difficult or even impossible to apply.

Time and experience have shown that the simple association of recruitment with cochlear pathology and absence of recruitment with neural pathology is invalid. There appears rather to be a continuum between the extremes. Measurement of recruitment is now seen as one of a number of tests that helps in localizing a lesion rather than as a definitive diagnostic tool.

**Acoustic reflex decay**

The phenomenon of tone decay has been known and investigated for upwards of 30 years. The perceived loudness of a sustained tone just above the threshold remains virtually constant over time for an individual with normal hearing. In an individual with a retrocochlear lesion, a tone at the same level may fade into inaudibility in seconds. Anderson, Barr and Wedenberg (1970) reported an equivalent effect in the acoustic reflex. In an individual with normal auditory function a low frequency, 500 or 1000 Hz, stimulus tone at an intensity 10 dB above the stapedial reflex threshold will produce a contraction of the stapedius muscle that is sustained over many seconds or even minutes. In individuals with tumours of the eighth nerve they observed that the response decayed rapidly. A decay to half of the initial magnitude of contraction in 4 seconds or less was found to be strongly associated with retrocochlear pathology.

As with recruitment testing, a major benefit of this type of test, especially in children, is that it does not involve the subject in difficult decision making: it is objective. The time course of the reflex response can be recorded and the rate of decay observed.

**Non-organic hearing loss**

Non-organic hearing loss is a not uncommon phenomenon in children, particularly girls, between the ages of 8 and 14 (McCanna and Delapa, 1981; Ward, 1984). Measurement of acoustic reflex thresholds may help in demonstrating a non-organic element in a presenting hearing loss. As previously noted, the acoustic reflex threshold (ART) for a normal hearing individual is 85 ± 10 dB. With increasing sensorineural hearing loss, the difference between auditory threshold and ART diminishes, but does not normally fall below 10 dB except for very severe losses.

A non-organic hearing loss may be suspected if the ART is less than 10 dB above the air conduction threshold. It is almost certainly established if the ART is at a lower intensity level than the pure tone threshold.
Establishing correct gain and output levels for hearing aids on infants and young children is fraught with difficulty. McCandless and Miller (1972) suggested that since the ART and loudness discomfort level for some types of acoustic stimuli - especially speech - were at approximately the same levels, the ART might be used as an objective method of indicating the upper limit of usable amplification from a hearing aid. The technique employed in this procedure is to place the subject in front of a loudspeaker (at, say, 1 metre distance) and stimulate with continuous speech at a level of approximately 70 dB. The aid is placed in the ear in which it is to be worn, complete with individual earmould and with the controls of the aid in the intended settings.

The probe of the admittance measuring system is placed in the opposite ear after verifying that there is no conductive loss and that stapedial reflexes can be elicited. The gain of the aid is then increased until the intensity peaks of the speech just begin to produce stapedial muscle contraction. If further gain is needed, then peak clipping or compression can be introduced such that the peaks of speech activity remain just at the level of reflex elicitation.

Tonisson (1975) described how the effective gain of a hearing aid could be measured from reflex data. In the first stage of testing the subject faces a loudspeaker at a distance of approximately 1 metre. The hearing aid is not worn and an admittance probe is placed in the ear opposite to the potentially aided ear. The ARTs are measured in this free-field situation for a range of frequencies spanning the amplification range of the aid. The aid is then fitted and adjusted to normal level and the measurement of the ARTs is repeated. The reduction in gain of the loudspeaker amplifier is the same as the gain in situ of the aid.

Unfortunately, the technique is time consuming and demanding on the subject's patience. In-the-ear pressure measurements, while not exactly indicating the insertion gain of an aid, are so much simpler to effect, especially with children, that the Tonisson method is now used only rarely.

**Summary**

Admittance measurement has been the most important development in audiology in the last 20 years. Used as a test battery comprising tympanometry and acoustic reflex measurements, both contra- and ipsilaterally elicited and measured, it is a source of valuable information in virtually every type of auditory disorder. It is a simple, quick procedure to employ. It is non-invasive. It is readily acceptable to the great majority of subjects from infancy to old age. The importance and value of admittance measurement in children was stated by Jerger et al (1974c) as 'the single most powerful tool at our disposal in pediatric evaluation. It cannot, however, stand alone. It can be interpreted successfully only in combination with some independent assessment of sensitivity level. When this condition is met, the combination leads to a significant advance in the sophistication of pediatric audiological assessment.'